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Implications of Quark-Lepton Symmetry for Neutrino Masses and Oscillations

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Abstract

We identify a plausible scenario based on quark-lepton symmetry which correlates long baseline oscillations with maximal mixing to sterile neutrinos. The implication for the Sudbury Neutrino Observatory (SNO) is that the neutral current signal will be found to suffer the same suppression from the Standard Solar Model prediction as obtains for the charged current signal. Flavor mixing among active neutrinos is expected to occur on shorter baselines with smaller mixing amplitudes.

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A principal feature of all of the experimentally known fundamental fermions[1] may be summed up in the following manner: The fermions may be grouped into three “families”, conventionally assigned by mass, consisting of two color triplets of quarks, one with electric charge $+2/3$ and the other $-1/3$, one lepton with electric charge -1 , their antiparticles and a neutrino. Each “family” of these fermions fills out fifteen $(\frac{1}{2}, 0)$ representations of the Lorentz group. Fourteen of these come in pairs with conjugate color and (electric) charge quantum numbers so that they may be reconstructed into seven Dirac bispinor representations. This is accomplished by using charge conjugation under the Lorentz group¹ to convert one member of each pair into the requisite $(0, \frac{1}{2})$ representation[3]. Despite this construction, and the fact that these pairs are not conjugate in their electroweak quantum numbers, the Lagrangian of the Standard Model (SM) does not intrinsically violate conservation of the weak interaction quantum numbers, courtesy of the chiral projections included in the interactions.

The exceptional case is that of the neutrino, which has no known partner representation. That such a partner should exist has long been suggested[4, 5] and is especially evident in “vector-like” Grand Unified Theories (GUTs). A satisfactory explanation of the stringent bounds on the mass of each of the three different flavors of neutrinos has been developed in this context in terms of the so-called “see-saw” mechanism[6]. This mechanism postulates that since the missing partner $(\frac{1}{2}, 0)$ representation carries no SM quantum numbers at all, and so is “sterile” with respect to all SM interactions, it may naturally acquire a large (GUT scale) Majorana mass. While the usual (active) $(\frac{1}{2}, 0)$ representation could also, in principle, develop a Majorana mass, the associated scalar field must carry weak isospin, $I_W = 1$, so that mass is usually assumed to be zero. The effect of this is to suppress the induced Majorana mass of the neutrinos active in the SM from the value common for Dirac fermion masses in the SM by a factor of the ratio of such masses to something very roughly on the order of the GUT-scale mass².

¹This should not be confused with the larger CP operation used earlier in connection with Majorana objects [2].

²Note that, in the usual discussions of the “see-saw”, the mass term that couples the active $(\frac{1}{2}, 0)$ representation to itself as a Lorentz charge conjugate $(0, \frac{1}{2})$ representation is referred to as m_L while the similar term for sterile neutrinos is referred to as m_R . Although that notation is natural under the assumption of Dirac neutrinos, here, since the neutrinos under discussion are massive Weyl (Majorana), that identification can lead to confusion. Hence, we use “active” and “sterile” throughout this paper.

While the prospect of providing a “natural” explanation for the small scale of active neutrino masses is pleasing, there is no principle requiring that the sterile mass be large. Here we discuss an equally valid scenario based on a view of quark-lepton symmetry, which is subject to a general experimental test that will soon be undertaken.

We start from the facts that the known Dirac fermion masses span a range of almost six orders of magnitude and that those of the neutrinos must be at least five to six orders of magnitude smaller still. We allow for the possibility that the true origin of these masses is still not understood and set aside the see-saw. We next recall that it is charge-conservation, for various charges, which eliminates the possibility of Majorana mass terms for each of the fourteen spinor representations that make up the known Dirac bispinors.

Now we recall an old conjecture[8]: That there is indeed a $(\frac{1}{2}, 0)$ representation for a sterile neutrino to form an eighth pair with the known active neutrino for each generation (or family) of fermions. Recalling that all other individual fermion number (baryon number, muon number, etc.) violations seem to be strongly suppressed, we are led to examine the possibility that this is true for neutrinos as well. This leads naturally to the conclusion that, while the sterile neutrino may have a Majorana mass, it should be expected to be small compared to the Dirac mass available to the pair of neutrino representations which can be formed into a Dirac bispinor. We must then simply accept the fact that the Dirac mass for this bispinor is, itself, very small to satisfy experimental constraints, although there are interactions which could exist that would modify the interpretation of these constraints[7].

Many have conjectured[9] that there should be some parallel (for example, right-chiral interaction) quantum number so that some sort of neutrino number remains. A related point has been made by Cahill[10], that a Majorana neutrino mass would violate lepton number (L) conservation, and hence also the difference between that and baryon number (B). The experimentally reported suppression of proton decay[11] provides strong support for an assumption that matrix elements for B-L violation are extremely tiny. Thus, we consider it viable to investigate the implications of the point of view that the Majorana mass terms of neutrinos are also quite small compared to Dirac neutrino mass terms.

This very general scenario leads to a quite well-defined class of predictions for neutrino properties and experiments. Denoting the Dirac mass connecting

the active and sterile neutrinos by M and the Majorana mass of the sterile neutrino by m , the conjecture that $m \ll M$ leads to the conclusion that the neutrino states are pseudo-Dirac.³ That is, the neutrino field eigenstates will be a pair of almost degenerate states and a neutrino will propagate almost as if it were a Dirac fermion. However, with a long oscillation length, it will transform between the active and sterile components, with almost *maximal* mixing (due to the almost complete degeneracy of the resulting Majorana mass eigenstates). This would be most simply expected to be true for each neutrino type separately. (See also Ref.[10].)

The immediate implication is that when maximal mixing is observed in neutrino oscillations, it will be between active and sterile types. Hence, the long baseline from the Sun leads to the conclusion that if the signal diminution observed in solar neutrino experiments[13] is due to vacuum neutrino oscillations, then the oscillation that is occurring is from active electron neutrinos to sterile (anti)neutrinos. It follows that the SNO experiment[14] is predicted to observe a reduction in the neutral current signal equal to that already found in the charged current signal. This prediction has also been made in Ref.[10].

Similarly, in the observed atmospheric oscillations[15], the long baseline suggests that the oscillation is from muon to sterile neutrinos. Although this is not favored by the current data set, neither is it inconsistent at present. The scenario discussed here predicts that additional data will find a diminishing signal for active-active oscillation.

We should, however, note a possibility which is difficult to encompass within unified models, but may nonetheless occur: The conjugate partner to the active neutrino representation of one family may be the active neutrino representation of a different family[12]. This would appear to violate quark-lepton symmetry and leaves one uncertain about whether or not there must be sterile partner representations. However, this possibility matches more closely with the preferred interpretation of the observed atmospheric oscillations[15], if the pair of families involved are those of the muon and tauon. Note that

³Here we use pseudo-Dirac to mean a pair of Majorana neutrinos with masses so nearly degenerate that, for many purposes, the linear combinations appropriate to a particle and an antiparticle are, to a good approximation, eigenstates of the mass matrix. This, we believe, is the general usage[8]. Wolfenstein introduced the term[12] to refer to a particular model in which the two $(\frac{1}{2}, 0)$ representations used to produce the Dirac bispinor were both active under the weak $SU(2)$, but were coupled to different charged leptons.

this still implies that the SNO experiment[14] would observe the same reduction of the neutral current signal as of the charged current signal because the solar neutrino oscillation would still necessarily involve a sterile neutrino partner. This conjecture raises the question of whether or not some vestige of quark-lepton symmetry obtains in the form of two additional sterile neutrino representations that mix only with each other, perhaps still forming a pseudo-Dirac bispinor.

We also note that there is the possibility of a modified “see-saw”, in which the sterile neutrino mass matrix in family space may have a large scale but a rank less than three. In this case one or two of the families may have neutrinos that are poorly described as pseudo-Dirac without affecting the remaining families. For example, if the rank is one, there are two zero eigenvalues of the m matrix, were it diagonalized by itself. The embedding of that matrix in the larger mass matrix for neutrinos can easily change two Dirac neutrinos into pseudo-Dirac neutrinos, or could lead to Majorana neutrinos with masses well-separated on the scale of the Dirac masses.

A priori, no definite predictions are made for flavor oscillations of the type reported to be observed by the LSND collaboration[16]. However, as the Dirac mass terms are larger than the Majorana mass terms in the particular scenario discussed here, and the Dirac mass terms may be presumed (on the basis of quark-lepton symmetry) to be analogous in structure to those found in the quark sector, flavor mixing should be expected to occur with shorter oscillation lengths and modest mixing amplitudes, i.e., much less than maximal. This is certainly consistent with the experimental reports[16, 17, 18] to date. Additional support for this scenario of small flavor mixing between pseudo-Dirac neutrinos may be found in recent discussions of possible interference effects modifying the end point spectrum in Tritium beta decay[19], when taken in combination with existing limits[20] on Majorana neutrino masses from neutrinoless double beta decay experiments.

Finally, we conclude that the strength of the neutral current signal of the SNO experiment is crucial to determining the viability of any pseudo-Dirac bispinor scenario.

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